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Conduit Ground Adapters (CGA) for Electromagnetic Interference/ Electromagnetic Pulse (EMI/EMP) Protection: The Model and Validating Measurements Using Heliax Cable

A Paper Presented at the 1988 IEEE International Symposium on EMC

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Preface

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"Conduit Ground Adapters (CGA) for Electromagnetic Interference/Electromagnetic Pulse (EMI/EMP) Protection: The Model and Validating Measurements Using Heliax Cable" (D.S. Dixon, R.M. Showers, J.E. Richie) presents a theoretical model for a conduit ground adapter. The model, inherently adaptable since it is a model, explains the major features of the shielding effectiveness characteristic of such devices as documented by experimental tests.

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CONDUIT GROUND ADAPTERS (CGA) FOR ELECTROMAGNETIC INTERFERENCE/ELECTROMAGNETIC PULSE (EMI/EMP) PROTECTION: THE MODEL AND VALIDATING MEASUREMENTS USING HELIAX CABLE

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1.0 INTRODUCTION

Conduit Ground Adapters (CGA) are presently being developed by various commercial and military organizations to provide a 360 degree, low impedance ground termination for metallic shield conduits. The need to provide this low impedance, waterproof, pressure proof, corrosion resistant, long term ground over the frequency range from 10 kHz to 100 MHz provides a significant design challenge to electromagnetic and mechanical design personnel.

The earlier successful development of a high performance Shield Ground Adapter (SGA) [1], [2] was significantly aided by the development of an electromagnetic model for the SGA. This model enabled the performance of the SGA to be improved by up to 35 dB. A similar model development effort was begun early in the CGA development effort to ensure that the CGA performance could be predicted and therefore improved and/or modified when necessary.

The CGA has a similar purpose to that of the SGA; however, there are significant differences in the construction details of these devices. The SGA is designed to be attached to a shield at the point of hull penetration and to remove the currents induced on the part of the shield external to the hull so as to prevent them from appearing on the part of the shield within the hull. In the case of the CGA, at the point of penetration the shielded cable passes entirely through the aperture without direct connection. The conduit itself entirely encircles the shield of the cable. Both the SGA and CGA depend upon having a low resistance between either the shield or the conduit and the hull. However, because of the different arrangements they may be expected to have somewhat different properties.

2.0 DEVELOPMENT OF MODEL

Figure 1 shows the typical physical arrangement of a conduit enclosed shielded cable. In this figure it is seen that the conduit runs from the termination point of the protected cable to the bulkhead. The bulkhead penetration is usually made by means of a kickpipe into which the conduit is threaded by means of adapter hardware. At the other end the conduit is usually short circuited to the shield of the protected cable. The high conductivity of the conduit and the desired low resistance at the kickpipe joint combine to shunt the currents induced on the conduit (on the portion to the left of the bulkhead in figure 1) to the bulkhead so as to avoid either leakage or coupling of this current to the equipment in the protected space to the right of the bulkhead on this figure.

2.1 PERFORMANCE CRITERIA

The performance of the CGA is measured in terms of the effectiveness with which it achieves its purpose of avoiding any coupling of current through the bulkhead. It can be evaluated in terms of either sine wave characteristics, or, if used for protection against EMP, in terms of its response to such pulses. The work here has been directed to the sine wave characteristics. This has the advantage of providing a direct indicator of the parameters of the system that affect its performance. In the case of pulse measurements it may be more difficult to associate performance with construction details. An analysis of performance in terms of a simulated EMP has been performed.[3]

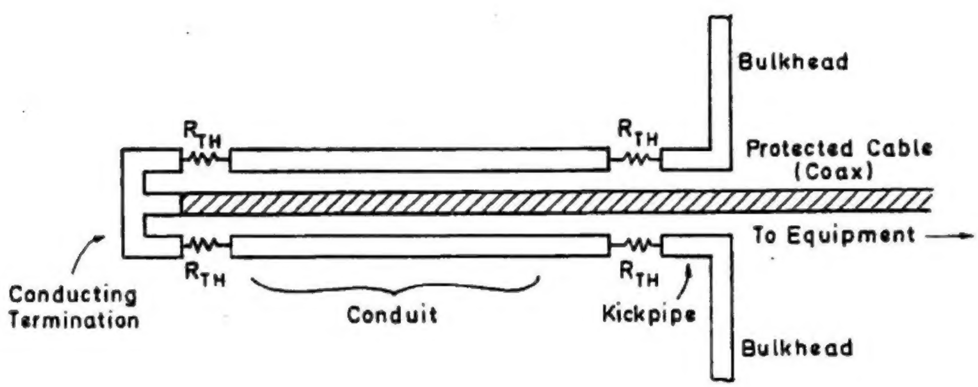


Figure 1. Physical Arrangement of a Conduit Enclosed Shielded Cable

2.2 SHIELDING EFFECTIVENESS

One can define the shielding effectiveness at any particular frequency as the ratio of the total current impressed on the outer surface of the conduit to the current on the protected cable at the point where it enters the bulkhead. It can vary considerably with frequency as a consequence of the varying impedance characteristic of the configuration: at very high frequencies the lengths of the cables and conduits involved can become appreciable fractions of the wavelength, causing rapid variation of impedance with frequency.

For the purpose of comparing different CGAs, it is best to define a representative configuration. In order to standardize impedance, the conduit is arranged as the inner conductor of a coaxial transmission line by placing a circular cylinder around the conduit and fastening it rigidly to a plane surface simulating a bulkhead. Likewise, the output line can be arranged so that it is the center conductor of a coaxial structure. The coaxial structures then have definable characteristic impedances, and termination impedances can be defined for them.

In order for the CGA to work properly, the end of the conduit opposite the kickpipe must be grounded to the shield of the coaxial cable. Otherwise, the device connected to the coaxial cable at that end will couple interference energy directly onto the cable. At the output end of the cable it is common practice to use a load of 50 ohms. However, at low frequencies a short circuit termination is more realistic. The configuration analyzed is shown in figure 2. In this figure we place a driving voltage between the outer cylinder and the left end of the conduit and observe the current from the energy source driving that point; we then compare it with the current on the coaxial cable beyond the bulkhead. When the ends of the structure shown in figure 2 are properly terminated it resembles a standard triaxial test configuration.

2.3 FREQUENCY DEPENDENCE OF THE MODEL

Although there is little practical concern about the effectiveness of the CGA for an applied direct current, it is of interest in connection with performance analysis. Note that at dc the ratio of the current applied by the external generator to the current on the protected cable is a simple function of the resistances of the two alternate current paths. The resistance of the conduit path consists of 1) the resistance of the conducting termination, plus 2) that of the conduit plus any mounting resistance due to threads or other contacts at both ends of the conduit, plus 3) the resistance in the bulkhead itself (which should be negligible). The resistance of the protected cable will depend primarily upon the resistance of the cable shield plus any termination resistance. Typically, one can expect the resistance of the protected cable shield to be somewhat higher than that of the conduit, perhaps by as much as an order of magnitude, in which case the shielding effectiveness at direct current would be of the order of 20 dB. Laboratory measurements have indicated shielding effectiveness of that order.

As the frequency increases two effects take place. One is due to the inductance of the individual conductors, i.e., of the conduit and that of the protected cable. The second is the skin effect, which causes current to flow preferentially on the outer surface of the conduit. Thus, one would expect the shielding effectiveness to increase exponentially once the skin effect phenomenon becomes significant in the conduit. Then skin effect dominates inductive effects. The shielding effectiveness obtainable will be limited, however, by the contact resistances at the conduit connections. Previous work on the SGA has shown that thread resistance, which may be of the order of only 10 or 100 micro-ohms, will not be frequency dependent and therefore will produce an ultimate limit on the performance of the adapter. Its actual value, however, is critically dependent upon construction details.

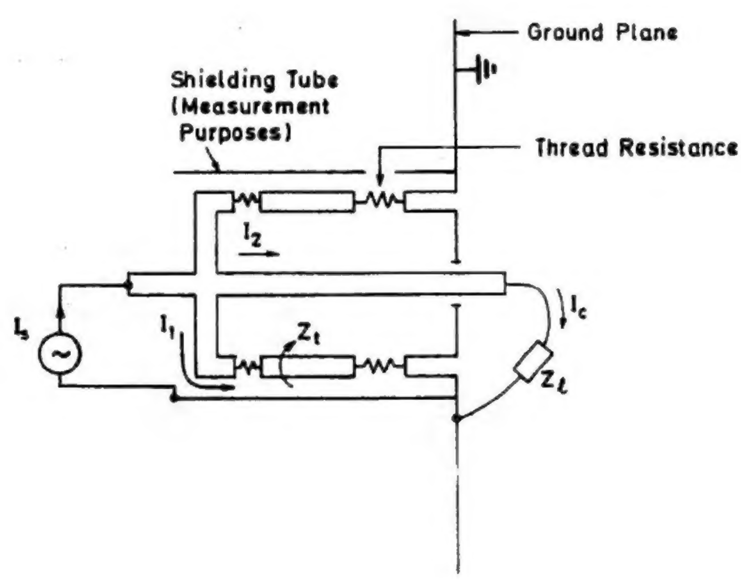


Figure 2. CGA Analysis Model

If the performance of the adapter is evaluated with a 50 ohm termination to the shield of the protected cable within the protected area, the low frequency performance of the adapter is considerably modified. With this termination the shielding effectiveness is given by the ratio of this termination resistance, that is, 50 ohms, divided by the sum of the resistance of the conduit itself and the thread resistances. Thus, at low frequencies the shielding effectiveness would be expected to be 80 dB or greater, and the skin effect phenomenon would become significant at somewhat higher frequencies than occurs with the short circuit termination.

2.4 MATHEMATICAL MODEL

Consider the arrangement of the CGA shown in figure 2. The shielding effectiveness (SE) is defined as I_s/I_c. The objective is to calculate SE as a function of frequency for $Z_\ell = 0\ \Omega$ and $Z_\ell = 50\ \Omega$. Note that on the left hand side of the structure the current I_s splits into two parts, I_1 and I_2. The inner current I_2 (which, at frequencies below about 30 MHz, is equal to I_c) causes a voltage drop across the inner conductor equal to the combined resistance, inductance, and load impedance drops:

$$V_{in} = [R_2(f) + j\omega L_2(f) + Z_\ell]I_2 = Z_2 I_2 \qquad (1)$$

where R_2 and L_2 are the self resistance and inductance of the center conductor. R_2 and L_2 are shown as varying with frequency due to skin effect. Correspondingly, the voltage drop V_{out} on the outer conductor is:

$$V_{out} = [R_1(f) + R_{TH} + j\omega L_1(f)]I_1 = Z_1 I_1 \qquad (2)$$

where R_1 and L_1 also vary with frequency and R_{TH} is the thread resistance, which is assumed not to vary with frequency. Assuming that at dc and low frequencies $V_1 = V_2$, i.e., the conduit and the cable are shorted together and therefore at the same potential at the far end, the shielding effectiveness then becomes:

$$SE = \frac{I_s}{I_c} = \frac{I_1 + I_2}{I_2} = \frac{Z_1 + Z_2}{Z_1} \qquad (3)$$

As the frequency increases, the constant potential concept is less tenable. As skin effect becomes important, the potential V_2 is better defined in terms of the surface transfer impedance and thread resistance of the outer conductor. Accordingly, (1) becomes:

$$V_{in} = [Z_t\ell + R_{TH}]I_1 = [R_2(f) + j\omega L_2(f) + Z_\ell]I_2 \qquad (4)$$

or

$$Z_3 I_1 = Z_2 I_2$$

$$SE = \frac{I_s}{I_c} = \frac{I_1 + I_2}{I_2} = \frac{Z_3 + Z_2}{Z_3} \qquad (5)$$

The surface transfer impedance Z_t is given by [4]

$$Z_t = R_{dc}\,\frac{(1 + j)\,(\tau_0/\delta)}{\sinh[(1 + j)\tau_0/\delta]},\ (j = -1) \qquad (6)$$

where R_{dc} is the dc resistance of the outer conductor per unit length, and τ_0 is its thickness.

2.4.1 Model Calculations

The model proposed in (5) can be written (by substituting impedance variables):

$$SE = \frac{Z_t\ell + R_{TH} + R_2(f) + j\omega L_2(f) + Z_\ell}{Z_t\ell + R_{TH}} \qquad (7)$$

The values of thread resistance R_{TH} and load impedance Z_ℓ are assumed constant with frequency. The length of the cable is ℓ.

Of interest is the evaluation of the parameters $R_2(f)$ and $L_2(f)$ necessary for computer implementation of the model. For simplicity, the change in inductance L_2 with frequency is neglected.

The resistance $R_2(f)$, however, varies significantly with frequency, due to skin effect. Values of the ratio of R_{ac}/R_{dc} as a function of frequency are given graphically in figure 2 (p. 33 of reference 5) for both solid and tubular conductors, with the ratio of tubular thickness to diameter as a parameter. In the present analysis, a three line segment curve fit was used to approximate the actual frequency dependence. The value of this ratio is approximately 0.046 ($t \approx 0.05$ cm and $d \approx 1.088$ cm) for the inner conductor. The curve fit was used on the $t/d = 0.05$ curve, and the resistance values of R_2 for all frequencies were calculated using the curve fit approximation,

$$R_2 = \xi\, R_2(dc) \qquad (8a)$$

where

$$\xi = 1 \qquad \text{if } f<16 \text{ kHz}$$

$$= [0.004(x-225)] + 1 \qquad \text{if } f\geq 16 \text{ kHz} \qquad (8b)$$

and

$$x = [f/0.3152]^{1/2} \qquad (8c)$$

2.4.1.1 Load Impedance of 0 ohms. The shielding effectiveness, with $Z_\ell = 0$, is:

$$SE = \frac{Z_t\ell + R_{TH} + R_2(f) + j\omega L_2}{Z_t\ell + R_{TH}} \qquad (9)$$

At very low frequencies (less than 1 kHz), the inductance is insignificant; $R_2(f)$ is approximately $R_2(dc)$ (a measured value of 6.1 milli-ohms), and Z_t is approximately the dc resistance of R_1 (conduit).

By denoting the total resistance of the conduit as $R_c = R_1(dc) + R_{TH}$, the shielding effectiveness can be written:

$$SE = \frac{I_1 + I_2}{I_2} = \frac{R_c + R_2(dc)}{R_c} \qquad (10)$$

which is precisely the current divider relationship expected. The measured value of R_c is 0.582 milli-ohms. Thus, at low frequencies,

$$SE = \frac{0.582\ (10)^{-3} + 6.1\ (10)^{-3}}{0.582\ (10)^{-3}} = 21.2 \text{ dB} \qquad (11)$$

As the frequency increases, the inductance becomes significant, and $R_2(f)$ and Z_t increase and decrease, respectively, due to skin effect. Since Z_t is decreasing, the shielding effectiveness increases. Physically, skin effect is causing reduction of coupling through the conduit. The rise in SE is shown in figure 3. In the figure, the shielding, as predicted by the model, increases with frequency.

2.4.1.2 Load Impedance of 50 ohms. The shielding effectiveness, with $Z_\ell = 50$, is:

$$SE = \frac{Z_t\ell + R_{TH} + R_2(f) + j\omega L_2 + 50}{Z_t\ell + R_{TH}} \qquad (12)$$

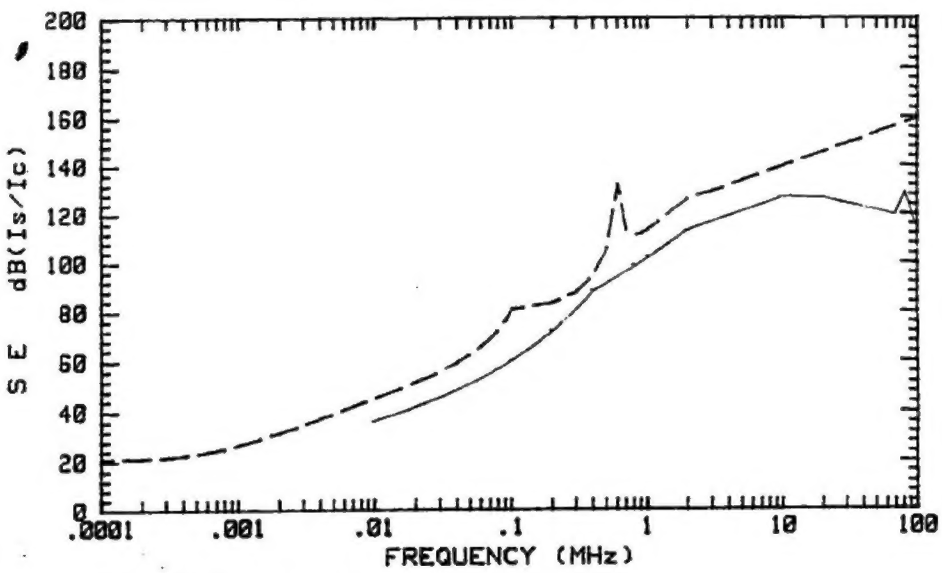
At very low frequencies, (9) holds; however, a 50 ohm resistor has been added to the center conductor, leaving a current divider of:

$$SE = \frac{R_c + [R_2(dc) + 50]}{R_c} \qquad (13)$$

$SE = 50/R_c = 98.7$ dB

as shown in figure 4.

As the frequency increases, skin effect causes a rise in SE, similar to the $Z_\ell = 0$ case. However, skin effect becomes appreciable only at relatively higher frequencies because when $Z_\ell = 50\ \Omega$, it dominates performance up to those higher frequencies.



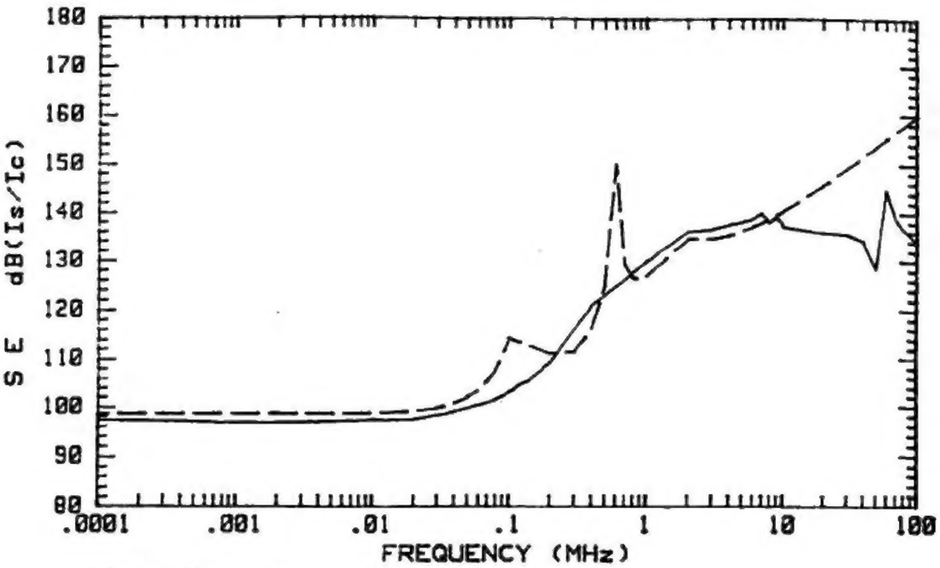
*Dashed line - theoretical
Solid line - experimental

Figure 3. Shielding Effectiveness (SE) of a CGA with 0 Ohms Load Impedance

As the frequency increases, the phase of the value of Z_t changes from its initial value of zero. The peaks in the theoretical curve occur when the phase of Z_t is π radians, since the voltage across the inner surface of the conduit is cancelling the voltage drop due to the thread resistance.

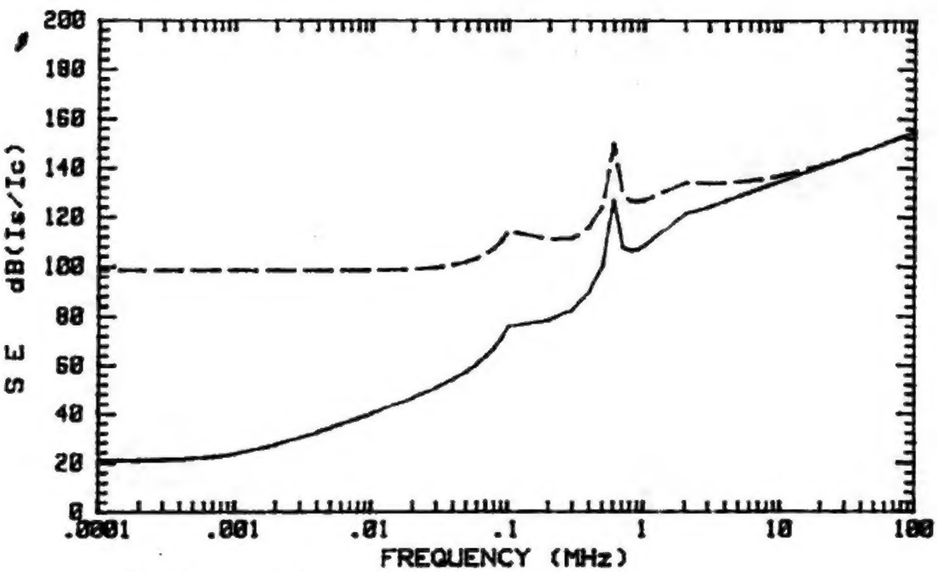
Once again, as frequency increases, the phase of Z_t causes peaks to occur. The peaks arise at the same frequencies as the previous case, since Z_t has not changed.

Figure 5 compares the model predictions for two cases, $Z_\ell = 0$ and $Z_\ell = 50$ ohms. This figure shows



*Dashed line - theoretical
Solid line - experimental

Figure 4. Shielding Effectiveness (SE) of a CGA with 50 Ohm Load Impedance



*Solid line - 0 ohms
Dashed line - 50 ohms

Figure 5. Comparison of Theoretical Shielding Effectiveness (SE) of a CGA with 0 Ohms Load Impedance and 50 Ohms Load Impedance

that the peaks occur at precisely the same frequencies since they are caused by the phase of the surface transfer impedance, Z_t. Also note that the effect of Z_ℓ is to raise the SE at lower frequencies.

3.0 EXPERIMENTAL RESULTS

3.1 TEST ARRANGEMENT

Although a finished model of the CGA was not available during the period of time in which the mathematical model was developed, laboratory measurements were made in order to validate the theory. The measurements were made on several types

of conduits, but the most detailed measurements were made on a 1 meter length of Heliax RG318U cable. This cable has a corrugated outer conductor that was used to simulate the conduit, and a center conductor approximately 3/8 of an inch in diameter that was used to simulate the shielded cable. The Heliax section was placed within a brass tube having a 3 inch outer diameter, a wall thickness of 1/16 of an inch, and a length of approximately 1 meter in a triaxial test configuration, as shown in figure 2. At both ends of the Heliax section a special fitting had been soldered to adapt the Heliax cable to a type N connector. The outer Heliax conductor was connected to the outside of the type N connector, and the center conductor was connected to the center pin jack of the connector. For the test circuit, according to figure 2, a shorting termination was placed on the left hand type N fitting and the currents I_s and I_c were both measured by means of current probes for $Z_\ell = 0$. For $Z_\ell = 50$ a coaxial cable was connected to the right hand type N fitting, which was terminated at a spectrum analyzer.

The measurement system illustrated by figure 2 was satisfactory for frequencies up to about 10 MHz. Above that frequency there was significant stray field coupling from the current probes.

In order to reduce leakage, a truly triaxial structure, shown in figure 6, was used. Note that in this figure, the right and left hand sides are interchanged when compared with figure 2. Here the signal generator could be connected to the BNC connector on the right end. The center pin of that connector is in contact with the shorting type N fitting, terminating the right hand end of the 1 meter length of Heliax RG318U cable.

Currents were measured both in terms of the voltage either across a 50 ohm resistor or directly, by a current probe connected at either end, as the case may be, but enclosed in an aluminum box with appropriate coaxial type connectors.

3.2 TEST RESULTS

The test results corresponding to the theoretical data shown on figures 3 and 4 are also shown on those figures. The agreement with the theory is quite good for both figures, with the following exceptions:

a) The experimental data do not exhibit the sharply peaked attenuation shown theoretically which is due to the 180° phase shift in the surface transfer impedance.

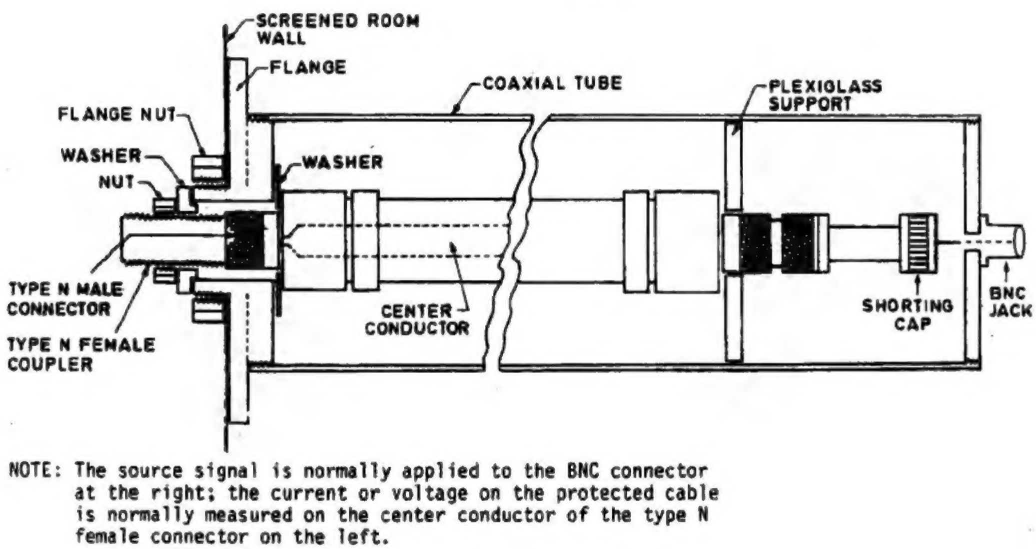
b) Significant deviations occur at frequencies above 10 MHz.

The first of these may be attributable to the corrugated nature of the structure of the conduit (the outer conductor of the Heliax RG318U cable). Unevenness of the 180° phase shifts frequency to vary slightly from one point to another along the length so as to strongly influence the depth of the null.

The second effect is believed due to the increasing impedance of the coaxial structure near quarter wave resonance, which occurs at 75 MHz. Time did not permit a correction in the model to account for this effect, but both experimental curves show SE levels somewhat below the theoretical values above 10 MHz, with rapid variations with frequency at about 75 MHz.

4.0 CONCLUSIONS

A model for the conduit ground adapter has been developed that explains the major features of the shielding effectiveness characteristic of such devices as documented by experimental tests. The results given here have yet to be validated by tests on an actual CGA. Because the device examined here was not an actual CGA, it may not fully represent the constructional features of the device. However, it is thought that any deviations in the structure from that assumed here could be properly modeled so as to produce an accurate theoretical basis for judging performance.



NOTE: The source signal is normally applied to the BNC connector at the right; the current or voltage on the protected cable is normally measured on the center conductor of the type N female connector on the left.

Figure 6. Triaxial Test Arrangement for Evaluating Shielding Effectiveness (SE) of a CGA

If thread resistance is neglected, a very strong rise in SE correlated with the magnitude of the surface transfer impedance of the conduit occurs. By including the thread resistance, the attenuation tends to almost saturate at frequencies above which it becomes dominant. However, it will continue to rise slowly due to the rise in the impedance of the center conductor with frequency.

5.0 REFERENCES

[1] D. S. Dixon, S. I. Sherman, and M. Van Brunt, "An Evaluation of the long term EMI performance of several shield ground adapters," Proc. IEEE Symposium on EMC, Atlanta, GA, p. 172, August 1985.

[2] R. M. Showers and S. Peters, "Development of models for the shield ground adapter," UPENN RPT MSEE-F-85-3, 31 December, 1985.

[3] Rockwell International Corp. Report, "Connector transfer impedance specification determination for shipboard EMP applications," Contract N00024-84-C-7121, December 1987.

[4] E. F. Vance, Coupling to Shielded Cables. Wiley, 1978, p. 113.

[5] F. E. Terman, Radio Engineers Handbook. McGraw Hill, 1943.

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